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TENSILE CAPACITY OF U-BAR LOOP CONNECTIONS WITH PRECAST FIBER REINFORCED DOWELS

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ABSTRACT

This paper describes an investigation of the tensile capacity of in-situ cast U-bar loop connections between precast concrete elements. The basic idea is to introduce a small precast cylindrical dowel of fiber reinforced mortar that fits into the bend diameter of the overlapping U-bars. The remaining part of the connection is cast in-situ with a regular mortar, which then encapsulates the precast dowel. Different dowel configurations have been investigated, including the use of steel or synthetic fibers with or without lacer bars placed within the precast dowel.

The experimental results show that use of a precast fiber reinforced dowel performs at a slightly lower load level, as compared to a connection grouted solely with regular mortar and reinforced with the same amount of transverse reinforcement. However, the load-displacement response of specimens with a fiber reinforced dowel is closer to ideal ductile behavior than that of the specimens grouted with regular mortar. The experimental results of the tensile tests are compared with calculations based on an upper bound plasticity model and satisfactory agreement has been obtained.

Keywords: Loop Connections, Tensile Capacity, Fiber Reinforced Concrete, Upper Bound Method

1. Introduction

Construction with precast concrete components is known to be fast, economic, and labor efficient. The challenge of constructing with precast components is in the assembly details where structural continuity and integrity have to be ensured, typically in a narrow construction zone. The connection design may be constituted by lap splices, U-bar loops, rebar welding or similar reinforcing details grouted by in-situ cast concrete or mortar. Common for all solutions is the demand for easy assembly, minimization of labor work, and structurally well performing solutions.

In some applications, the U-bar loop connection is preferred, as it requires the least work within the smallest construction zone and the performance of the connection is increased due to the superior anchorage properties of the loop bars (Mattock 1994). This connection type can be used to transfer tensile forces, bending moments or shear forces (FIB 2008) and the design is widely applicable from connections in bridge decks at intermediate piers (Jørgensen & Hoang 2013) to connection of vertical shear walls in buildings. In bridge deck applications over intermediate piers, the demand for sufficient tensile capacity is obvious as the connection appears in the tensile zone of the composite bridge girder. However, for shear wall systems, where the joint interface often is indented, the tensile capacity of the connection is required to activate the full load carrying capacity of the indentations and to ensure connectivity of the joint during shear deformation.

The loop bar connection consists of bent U-bars protruding from the precast element and overlapping the loops of the adjacent element. To obtain a strong connection, the overlapping loop area is reinforced and the joint area is grouted on-site with a concrete or a mortar. The connection is preferably designed for reinforcement yielding and not concrete failure. A relatively limited amount of work has been published on the behavior of loop connections in tension. Leonhardt et al. (1973) was the first to publish test results, investigating the required overlapping area of the U-bars in order to obtain yielding of the U-bars and not concrete failure of the grout material. The tests were designed as a 2-to-2 connection where the overlapping loops were placed closely together. The design is an example of a *symmetric unit* (Gordon 2006) where the main reinforcement is placed symmetrically about the line of loading. Gordon tested both symmetric 3-to-4 connections and non-symmetric connections and reported that non-symmetric specimens

are unsuitable for pure tension due to in-plane rotation of the specimen. The remaining experimental work on symmetric connections include the work of Ong et al. (2006) who tested 1-to-2 designs and compared to a theoretical strut-and-tie model and Jørgensen & Hoang (2013) who tested 2-to-3 specimens and provided an upper bound plastic model. In the literature it is generally recognized that the overlapping area of the U-bar loops, the spacing of the loops, the strength of the joint material and, finally, the transverse reinforcement in the overlapping area influence the tensile capacity.

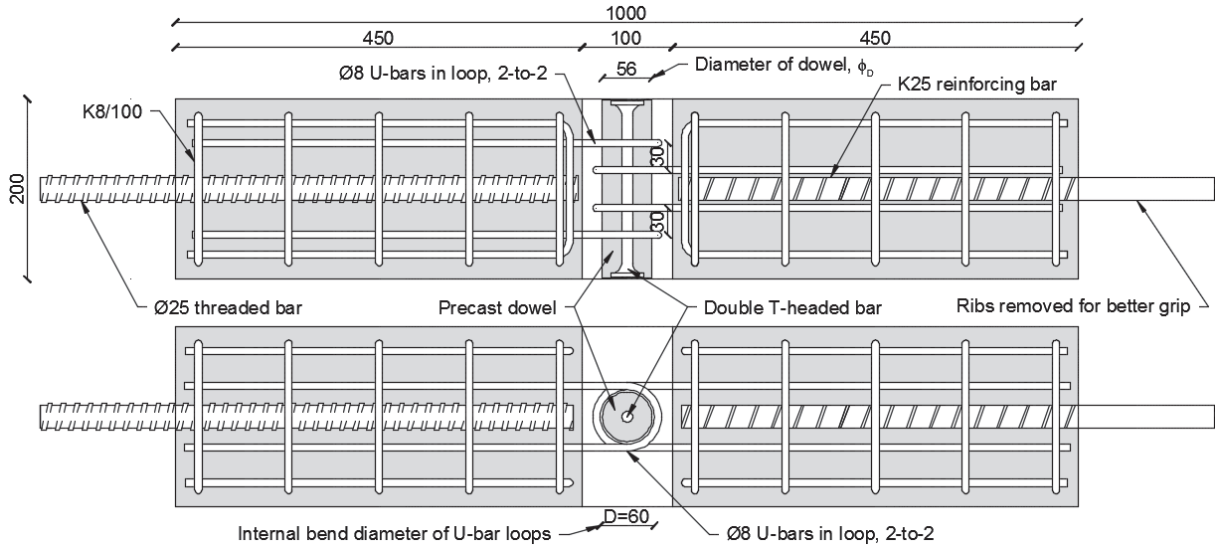


Fig. 1. Geometry of test specimens with a fiber reinforced dowel placed in the overlapping loop area

The transverse reinforcement is of special interest as the reinforcement area, the yield strength and the anchoring conditions influence the tensile capacity. Gordon (2006) tested a single connection with steel fiber reinforced concrete as replacement for rebars concluding that the fibers alone did not ensure a ductile behavior as the capacity decreased once the concrete material failed. This paper describes the tensile capacity of a symmetric 2-to-2 loop connection, see Fig. 1. The design investigates the use of a precast fiber reinforced dowel as reinforcement of the circular overlapping loop area while the remaining connection is grouted with regular low strength mortar. In addition, the paper presents a model for assessment of the ultimate capacity of the loop connection regarding concrete failure. The model is based on the upper bound theorem of rigid-plasticity accounting for the geometry of the connection.

2. Experimental investigation

The experimental program consisted of 27 specimens investigating the tensile capacity and the load-displacement relation of the reinforced loop connection. The overlapping loop area was reinforced with a precast fiber reinforced dowel with and without lacer reinforcement in shape of a double T-headed bar. A series without fiber reinforcement served as a reference. The program was divided into three series, as given in Table 1.

Table 1. Overview of experimental program

Series	No. of specimens	Precast Dowel	Fiber type	Shape	Length [mm]	Diameter [mm]
R	9	No	-	-	-	-
P	8	Yes	Polypropylen	Random	Random	-
S	10	Yes	Steel	Straight	12	0.4

2.1 Reinforcement configuration and material properties

Table 2 contains an overview of the tested specimens with their material properties. The fiber reinforced concrete mix was designed with small aggregate sizes due to the limited size of the precast dowel. For the

polypropylene fiber mix an aggregate size of maximum 2 mm was used and for the steel fiber mix and the regular mortar mix maximum 4 mm aggregates were used. The compressive strength, f_c , given in the table is related to the strength of the joint mortar for Series R and related to the strength of the dowel mortar for the remaining series. The compressive strength of the concrete in the prefabricated elements were in the order of 60 MPa and the grouting mortar in Series P and S were kept lower than the strength of the dowels as it was used as filling material outside the overlapping loop area; in this case, $f_{c,mortar}$ was around 16 MPa.

Table 2. Specimen details and test results

Specimens		Dowel		Lacer reinforcement		Loop reinforcement		$P_{u,test}$ [kN]
		ϕ_D [mm]	f_c [MPa]	ϕ_L [mm]	f_{yL} [MPa]	ϕ [mm]	f_y [MPa]	
R12	a,b,c	-	39.5	12	552	8	530	73.6 / 77.6 / 78.4
R14	a,b,c	-	39.5	14	562	8	530	76.4 / 79.2 / 88.0
R16	a,b,c	-	39.5	16	563	8	530	88.2 / 97.2 / 103.8
P	a,b,c	56 ± 2	39.0	-	-	8	530	30.5 / 33.0 / 36.4
P12	a,b,c	56 ± 2	43.0	12	552	8	530	52.0 / 53.0 / 53.8
P16	a,b	56 ± 2	43.0	16	563	8	530	67.8 / 75.9
S	a,b,c	56 ± 2	35.0	-	-	8	530	25.3 / 27.9 / 31.1
S12	a,b,c	56 ± 2	35.0	12	552	8	530	56.7 / 58.0 / 63.7
S14	a,b	56 ± 2	35.0	14	562	8	530	64.0 / 70.1
S16	a,b	56 ± 2	35.0	16	563	8	530	60.2 / 68.6

2.2 Geometry and fabrication

Each specimen consisted of two precast concrete elements linked by a loop connection, see Fig. 1. In each precast element a reinforcement bar was placed centrally in order to achieve precise centric loading conditions. The precast dowels were produced in advance. The mold used for the precast dowels consisted of polystyrene plates with mechanically drilled holes. The procedure of drilling frayed the edges and made the surface of the dowels rough, see Fig. 2(a).



(a) Precast dowel



(b) Positioning of dowel



(c) Without precast dowel

Fig. 2. Examples of (a) a precast dowel after demolding from polystyrene mold, (b) a precast dowel placed in the overlapping loop area and (c) the positioning of the lacer reinforcement in Series R

The surface improved the anchorage of the dowel to the remaining joint mortar. The dowel was produced with a diameter of 56 ± 2 mm leaving a tolerance of 4 ± 2 mm to the internal bend diameter of the loop bars. The overlapping area of the U-bar loops and the connection width were kept constant. For the specimens cast with regular mortar, Series R, the lacer bar was attached to the outer loop bars; see Fig. 2(c).

2.3 Setup and testing procedure

The tests were performed in a 500 kN servo hydraulic testing machine applying uniaxial tension to the centered bars in each of the two precast elements. The tests were performed as a displacement controlled quasi-static test with a rate of 0.5 mm/min followed by 4 mm/min after entering the post peak region. The specimens were positioned vertically, and in the lower end the ribs were removed from the reinforcement bar in order to ensure sufficient anchorage between the hydraulic grip and the bar. At the top of the specimen a connecting device was applied to accommodate any unintentional eccentricities and to ease the installation of the specimens in the testing machine, see Fig. 3. The load was applied through a spherically shaped nut which automatically centered the load.

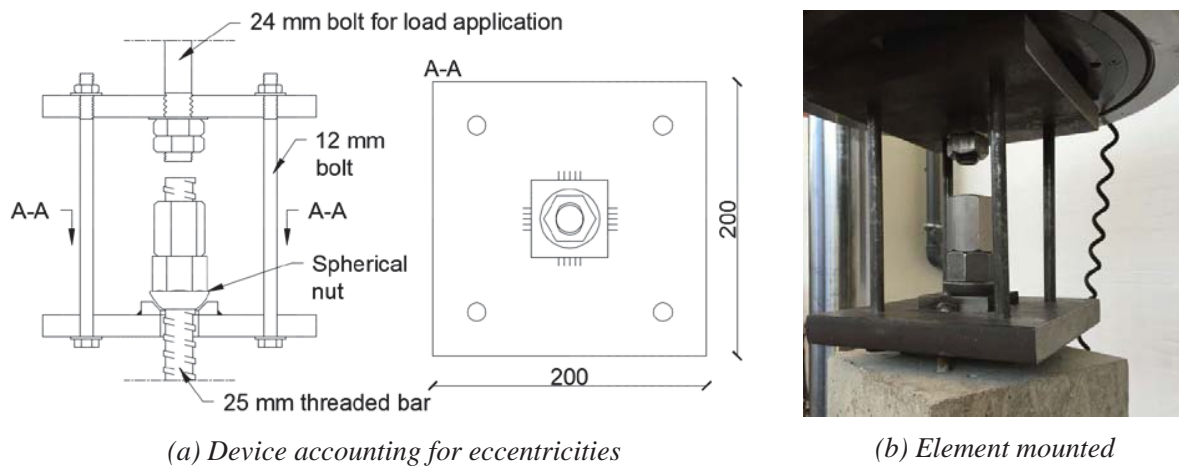


Fig. 3. Test device including (a) geometry and (b) test device with specimen prepared for testing

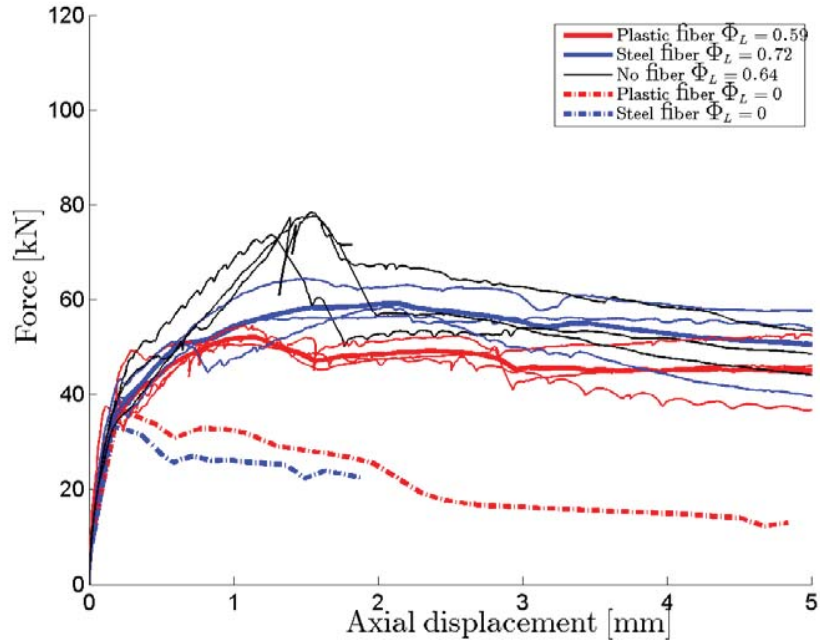
The relative displacements of the loop connection were monitored on the surface of the specimen using displacement transducers placed centrally on each side of the specimen. On the remaining faces high resolution digital cameras were used to record photos for digital image correlation (DIC). However, as a complex stress distribution developed in the loop connection, no accurate prediction of the cracking behavior could be measured on the surface. Consequently, the results of the digital image correlation were primarily used for verification of the displacement transducer measurements.

3. Experimental results

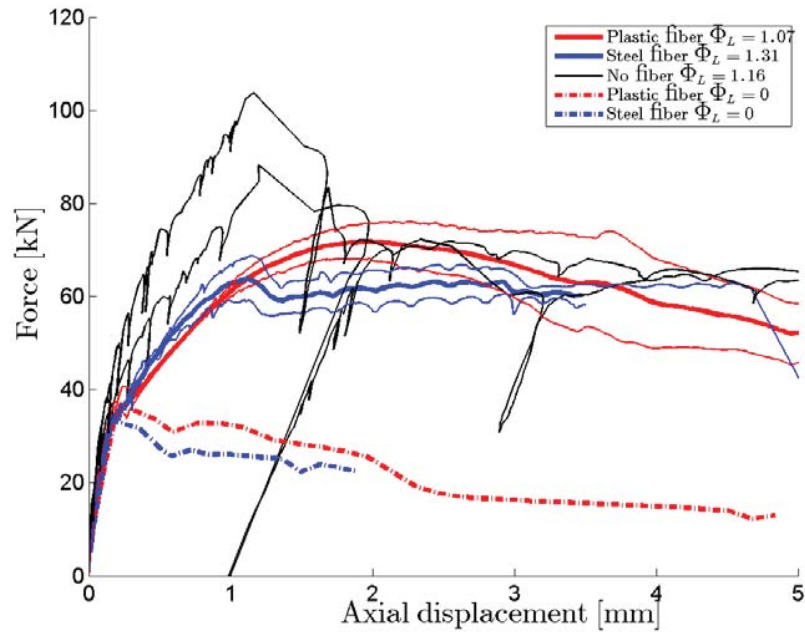
The experimental results are reported as load-displacement curves, where the axial displacement is taken as an average of the measurements from the displacement transducers. The displacement measurements from the transducers were confirmed by the digital image correlation. The general behavior of all specimens was a relatively stiff elastic response up to a certain point where cracking became visible on the surface of the connection. The results for the specimens reinforced with precast fiber reinforced concrete without lacer reinforcement identified this load level as the cracking load of the concrete material, see Fig. 4. The behavior was common to both specimens with precast dowels and with regular mortar, and thereby it constituted the point where the lacer reinforcement was activated. The ultimate load level reached after the initial cracking was dependent on the amount of lacer reinforcement. In general it was seen that an increasing reinforcement ratio led to an increased ultimate load.

Figure 4 contains the results of the specimens with $\phi 12$ mm and $\phi 16$ mm lacer reinforcement. For the specimens with a precast dowel the average of the test results are also given as bold curves. The average

of the results from the three specimens without lacer reinforcement is indicated as dashed lines. Besides the identification of the cracking load, it can be seen in the figure that the peak loads of the specimens with a precast dowel were not as high as for the connections cast entirely with mortar, however, the residual capacity after peak was comparable as the fiber reinforced specimens experienced a far less pronounced drop in load-deflection response at peak.



(a) $\phi 12$ lacer reinforcement



(b) $\phi 16$ lacer reinforcement

Fig. 4. Test results for specimens with lacer reinforcement

From the tests it was also found, that the two fiber reinforced configurations, Series P and S, performed similarly. It was found that the specimens without lacer reinforcement experienced a reduction in load level after the cracking load, whereas the lacer reinforced fiber dowels maintained a relatively constant load level.



(a) With precast dowel



(b) Without precast dowel

Fig. 5. Failure patterns for (a) a specimen with a precast dowel reinforced with polypropylene fibers and (b) a loop connection fully grouted with mortar and transversely reinforced with steel

Figure 5 contains pictures of the general failure pattern observed at a late stage of testing. For specimens reinforced with a precast dowel, the ultimate failure was governed by concrete failure in the dowel in terms of cracks extending from the contact point of the outermost loop of an element to the contact point of the outermost loop protruding from the adjacent precast element; see Fig. 5(a). Before this failure, the surrounding mortar had already spalled off. For the specimens with a connection solely grouted with mortar, the failure pattern was similar; however the geometry was much more complex as the mortar outside the overlapping area of the loops influenced the crack pattern. Figure 5(b) demonstrates the crack appearance between the loops while also revealing the correlation to the cracking of the remaining mortar.

4. Failure mechanism

From the observed failures, see Fig. 5, and the corresponding failure loads, it is indicated that the capacity of the joint material regarding concrete failure is less than the tensile capacity of the reinforcement loops. Furthermore it is indicated that the concrete yield lines between the loop bars dictate the capacity of the connection. As the overlapping loop area determines the total area of the diagonal yield lines, the capacity of the connection is also governed by this area, as suggested by Jørgensen & Hoang (2013).

In the following, an upper bound plasticity model for concrete failure of the examined connection will be presented. The concrete and the reinforcement loops are assumed to be rigid-perfect plastic materials obeying the associated flow rule. Furthermore the reinforcement is assumed to carry only axial loads, the concrete is assumed to have no tensile strength and the failure surfaces are as a simplification assumed as plane, represented by a linear yield line in a 2D representation. In Fig. 6(a) the simplified two-dimensional failure mechanism is shown and in Fig. 6(b) the relative displacements for the yield lines are indicated. Figure 6(c) represents the characteristic areas adopted in the calculations.

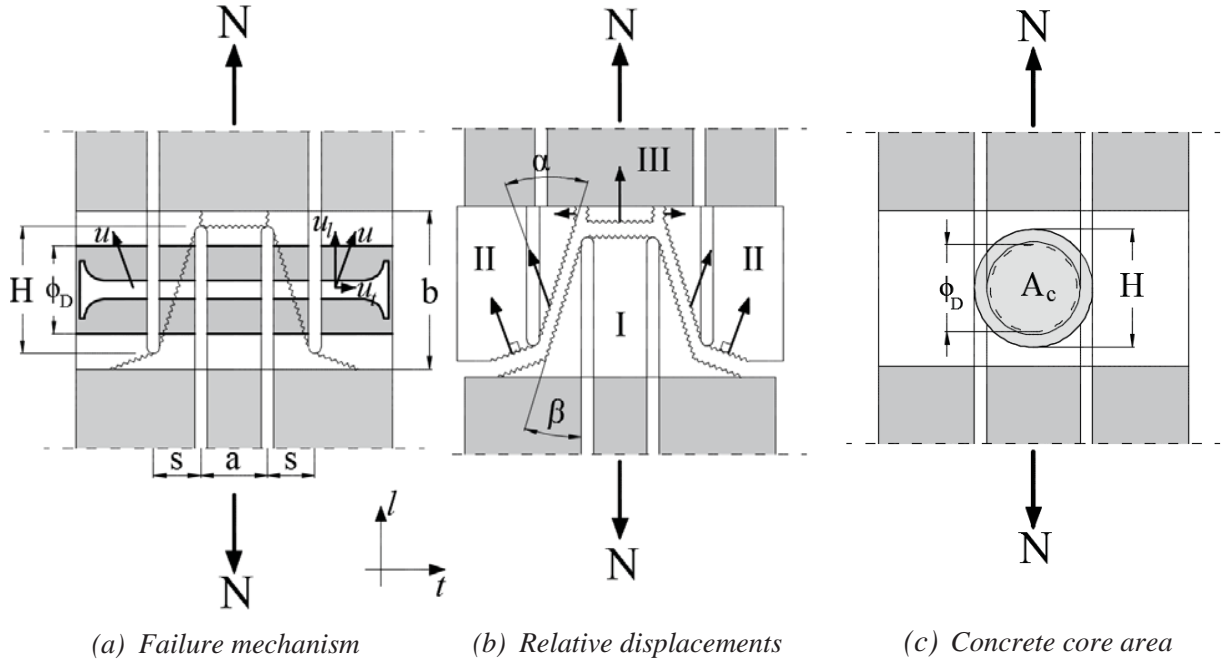


Fig. 5. Simplified failure mechanism (a) for tensile action on a loop connection, (b) a representation of the relative displacements in each yield line and (c) the characteristic concrete areas

The relative displacements are related in the following way:

$$u_i = |\mathbf{u}| \cos(\alpha - \beta) \quad \text{and} \quad u_t = |\mathbf{u}| \sin(\alpha - \beta) \quad (1)$$

Where α is the angle of the displacement vector to the corresponding yield line and β is the inclination of the yield line related to vertical:

$$\beta = \arctan\left(\frac{s}{H}\right) \quad (2)$$

4.1 Upper bound solution

The load carrying capacity is determined from the work equation, where the rate of external work and the rate of internal work performed in the failure mechanism are equated. The rate of external work performed by the axial load is given by:

$$W_E = Nu_i \quad (3)$$

The rate of internal work is constituted by contributions from dissipation in the concrete yield lines and in the lacer reinforcement crossing the yield lines. The contribution from the lacer reinforcement is given as:

$$W_I^S = 2A_{sL}f_{yL}u_i \quad (4)$$

The dissipation in a concrete yield line for a plane strain problem is given by (Nielsen & Hoang 2011):

$$W_I^C = \frac{1}{2}v f_c (1 - \sin \alpha) A_i |u| \quad \alpha \geq \varphi \quad (5)$$

Where A_i is the area of the yield surface, φ is the internal angle of friction and v is the effectiveness factor for concrete. It is necessary to introduce the effectiveness factor as concrete is not a perfect plastic material. The factor has not been established for the specific problem at hand, however in Jørgensen & Hoang (2013) the factor applied for beam shear problems was adopted. When dowel action is ignored and

the axial length of the overlapping area is chosen as the characteristic shear length, H , the effectiveness factor appears as:

$$\nu = \frac{0.88}{\sqrt{f_c}} \left(1 + \frac{1}{\sqrt{H}} \right), \quad f_c \text{ in MPa and } H \text{ in m.} \quad (6)$$

As the concrete is assumed to have no tensile strength, the contribution from the concrete yield lines outside the overlapping area is zero as the angle of the relative displacement vector is 90° , see Fig. 5(c) and Eq. (5). The capacity will thereby solely depend on the two diagonal yield lines between the adjacent loop bars protruding from each precast element. As the shape of the overlapping area is circular, the plane area of the yield line is given as:

$$A = \frac{A_c}{\cos \beta} = \frac{\pi}{4} \frac{H^2}{\cos \beta} \quad (7)$$

Equating Eqs. (3) with (4) and (5) the following upper bound solution is found:

$$\frac{N}{\nu A_c f_c} = \frac{1 - \sin \alpha}{\cos \beta \cos(\alpha - \beta)} + 2 \frac{\Phi_L}{\nu} \tan(\alpha - \beta) \quad (8)$$

Where the mechanical reinforcement ratio of the lacer reinforcement is introduced:

$$\Phi_L = \frac{A_{sL} f_{yL}}{A_c f_c} \quad (9)$$

The minimum of the upper bound solution is found for the following displacement angle:

$$\alpha = \beta + \arcsin \left(\frac{1 - 2 \frac{\Phi_L}{\nu}}{\sqrt{1 + \left(\frac{s}{H} \right)^2}} \right) \geq \varphi \quad (10)$$

From the optimal angle, it can be found, that the tensile capacity of the loop connection will be zero when no lacer reinforcement is present. This is of course due to the fact that the concrete is assumed to have no tensile strength.

From the geometry of the connection it can also be found, that an additional restriction is imposed on the displacement angle α . The displacement angle cannot be smaller than the inclination of the yield line, β , as such a situation would cause area II to move inwards, see Fig. 5(b). Considering these restrictions, the capacity can be summarized as:

$$\frac{N}{\nu A_c f_c} = \begin{cases} \sqrt{\left(\frac{s}{H}\right)^2 + \frac{4\Phi_L}{\nu} \left(1 - \frac{\Phi_L}{\nu}\right)} - \frac{s}{H} & \text{(a) for } \alpha \geq \varphi \text{ and } \alpha \geq \beta \\ \frac{\left(1 + \left(\frac{s}{H}\right)^2\right) \left(\frac{1}{\cos \varphi} - \tan \varphi\right) + \frac{2\Phi_L}{\nu} \left(\tan \varphi - \frac{s}{H}\right)}{1 + \frac{s}{H} \tan \varphi} & \text{(b) for } \alpha < \varphi \text{ and } \varphi > \beta \\ \sqrt{1 + \left(\frac{s}{H}\right)^2} - \frac{s}{H} & \text{(c) for } \alpha < \varphi \text{ and } \varphi \leq \beta \end{cases} \quad (11)$$

As the capacity of the connection is governed either by the concrete failure or tensile yielding of the loop bars, the capacity for the presented loop design will be given by:

$$N_U = \min \begin{cases} N & \text{Concrete failure as given in Eq. (11)} & \text{(a)} \\ 4A_s f_y & \text{Yielding of U-bars in tension} & \text{(b)} \end{cases} \quad (12)$$

As it can be seen, the solution is dependent on the internal angle of friction for the cementitious material used to fabricate the dowels or to grout the joint. If an internal angle of friction is chosen as the value for regular concrete, $\tan(\varphi) = 3/4$, the solution appears equal to the findings of Jørgensen & Hoang (2013). However, as the materials used for prefabrication of fiber reinforced dowels contain smaller aggregate sizes than regular concrete, the solution must be able to account for the actual value of the internal angle of friction of the grouting material.

5. Comparison of theory with test results

Figure 6 contains a comparison between the peak load observed in the experimental tests and the model presented. In the calculation a mean compressive strength of 39.5 MPa has been used and the same characteristic length of $H=0.076$ m has been used for all specimens in the determination of the effectiveness factor. The effectiveness factor was calculated to 0.65. The internal angle of friction was chosen as $\varphi = 37^\circ$ for the fiber reinforced material, Series P and S, and $\varphi = 30^\circ$ for the specimens without precast dowels, Series R.

For the specimens with fiber reinforced dowels, the surrounding mortar did crack and break off before the ultimate load was reached; hence it is assumed that the mortar did not contribute to the capacity at ultimate. As the precast dowel itself had a smaller diameter than the circular overlapping area, the inclination of the yield line, β , would be larger than presented in Eq. (2). For a more accurate strength determination, the characteristic height, H , was replaced by the diameter of the dowel, ϕ_D , changing the concrete area A_c and thereby the mechanical reinforcement degree. This was considered reasonable as the diameter of the dowel was close to the diameter of the overlapping area of the U-bars. However, Fig. 6(a) shows that the calculation underestimates the capacity, which is regarded the fact that the improved tensile capacity of the fiber reinforced concrete was not included in the model. Furthermore, the effectiveness factor for the fiber reinforced materials might attain a larger value than what has been utilized in these calculations.

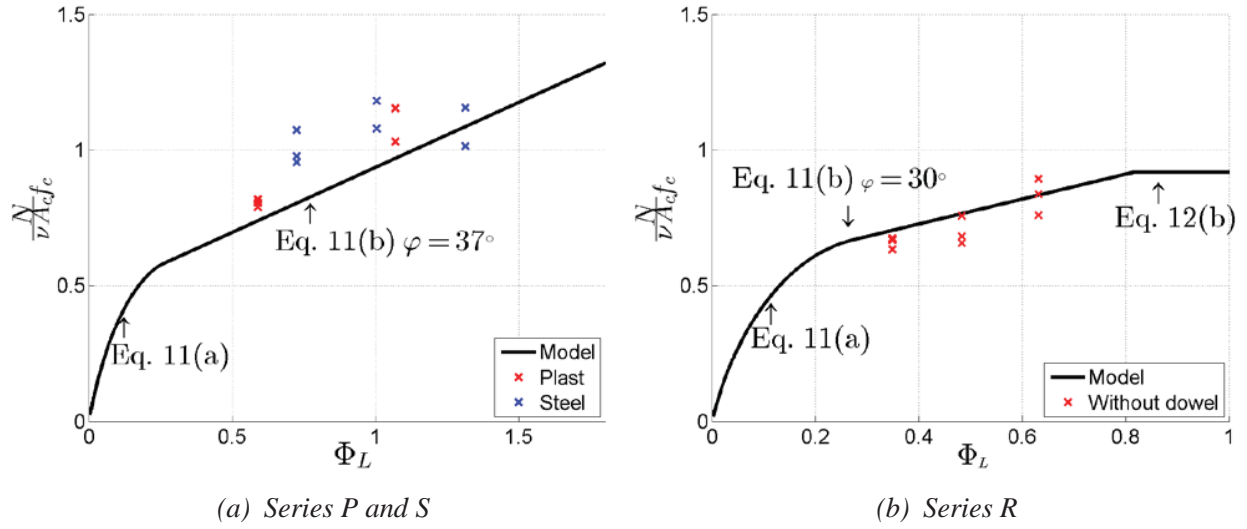


Fig. 6. Comparison of tensile capacity for (a) specimens reinforced with precast fiber reinforced dowels and (b) specimens with joint grout of regular mortar

The internal angle of friction is an important parameter in the theoretical calculation. For the fiber reinforced material the choice of $\varphi = 37^\circ$ seems appropriate to fit the tendency observed in the experimental tests, however as the aggregate sizes are small in the fiber reinforced concrete the internal angle of friction might in fact be smaller. Further studies are needed to verify this value.

For the specimens grouted with regular mortar with a maximum aggregates size of 4 mm, the internal angle of friction is believed to be reduced compared to 37° , which is the value normally adopted for regular concrete with larger aggregate sizes. The chosen value of 30° captures the development observed in the tests, however as the number of tests are limited, further research on this parameter is needed to verify current initial results. Furthermore it is well known that a mortar material behaves in a more brittle manner compared to regular concrete as the effect of aggregate interlocking is reduced. This could be accounted for by reducing the effectiveness factor; however the current initial tests do not warrant such a need.

6. Conclusions

The experimental program of the investigation reported on in this paper consisted of tension tests on loop connections reinforced with precast fiber reinforced dowels. The tests revealed a pronounced ductile behavior of specimens reinforced with precast fiber reinforced dowels compared to a connection grouted with regular mortar. The ultimate load level was lower than that in reference tests completely grouted with mortar; however the load displacement development was clearly ductile. Two different fiber materials were examined and no distinctive difference was observed between the two in terms of load-displacement responses. Tests on specimens with a fiber reinforced precast dowel without additional lacer reinforcement, revealed the transition point where additional steel reinforcement was activated.

In general, the presented upper bound solution captures the tendency in the tests regarding the concrete failure of the concrete core for increasing transverse reinforcement area. The tests on specimens with precast fiber reinforced dowels reveal a smaller ultimate capacity compared to a grouting without precast dowels. This is accounted for in the model by adjusting the area of the yield surfaces to the cross sectional area of the precast dowel. This predicts a conservative capacity as the tensile strength of the fiber reinforced composites is disregarded. This adjustment should only be used for precast dowel with a diameter in the same order of magnitude as the diameter of the overlapping loop area. For the specimens without precast dowels, the model captures the test results well, when choosing an internal angle of friction for the mortar of 30° .

Acknowledgements

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